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Analyzing streamflow changes: irrigation-enhanced interaction between aquifer and streamflow in the Republican River Basin

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Abstract

Groundwater-fed irrigation has altered surface and groundwater interactions, calling for conjunctive management of surface water and groundwater resources in many areas, including the Republican River Basin (RRB) in Midwest of the US, where agriculture heavily depends on irrigation. The decreasing flow trend recorded at the RRB gauging stations since 1950s reflects the synthetical effect of dynamic interactions between surface water and groundwater systems, which has been enhanced by groundwater pumping and irrigation return flow. This study uses a systematic modeling approach to analyze the conjunctive effects of pumping and return flow on streamflow. A watershed management model, Soil and Water Assessment Tool (SWAT), is modified and established for the Frenchman Creek Basin (FCB), a sub-basin of RRB, to examine the causes of streamflow changes. The baseflow component in SWAT is linked to aquifer storage so that the model can simulate the combined effect of groundwater pumping and irrigation return flow on natural streamflow. Results show that irrigation has not only depleted streamflow but also changed the flow pattern and seasonal variability. The changes can be decomposed into decrease in the slow component (baseflow) and increase in the fast components (surface and subsurface flow). Since the fast components are subject to higher variability than the slow component, the annual streamflow variability is amplified. Agricultural water use in this region also has changed the groundwater storage seasonal regime from the pattern of "summer-recharge and winter-discharge" in the past to "summer-discharge and winter-recharge" at present. This challenges the existing groundwater modelling which usually assumes fixed recharge pattern and rates.

1 Introduction

Irrigation has contributed to agricultural production increase during the past decades, and it has been the largest water consumption sector throughout the world, accounting

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for about 70 % of the global freshwater withdrawals and 90 % of consumptive water uses (Siebert et al., 2010). In the US, irrigation is located in the states where average annual precipitation is typically less than 20 inches and thereby is insufficient for crop consumption. As surface water resource is prone to be affected by climate variability and pollution, and needs infrastructure investment for storage (e.g., reservoir) and delivery (e.g., channels), groundwater has replaced surface water as the major water source in many places. In 2005, 13 arid or semi-arid western states consumed nearly 90 % of the groundwater used for irrigation, among which groundwater was the primary source for irrigation in Nebraska, Arkansas, Texas, Kansas, Mississippi, and Missouri (Kenny et al., 2009).

Groundwater-fed irrigation alters hydrological processes across a range of scales. The estimated global groundwater depletion since 1900 is equivalent to 12.6 mm rise in sea level, which accounts for more than 6 % of total sea-level rise (Konikow, 2011). Nonrenewable groundwater abstraction contributes approximately 20 % to the global gross irrigation water demand in the year of 2000 (Wada et al., 2012). At the regional scale, the rapid development of groundwater pumping after 1950s has changed the interactions of surface water and groundwater and caused water rights conflicts between surface water users and groundwater users in western states of the US (Gleeson et al., 2012; Sophocleous, 2010). At local scale, the changes in groundwater storage and flux affect terrestrial environment and fluvial biota (Alley et al., 2002). The interactions between groundwater and lakes, wetlands, estuaries, and oceans play an important role for the distribution of biota and biogeochemical processes, such as fish spawning area (Malcolm et al., 2008).

Moreover, the aggregation of the disruptions of local hydrological cycle by intensive irrigation has been found to affect the regional climate, which would further affect the irrigation requirement, leading to a feedback loop. Irrigation impacts land surface processes by altering the partition of energy and water through the interactions between soil profile, land surface flux and groundwater depth. Studies have shown that irrigation increases surface latent heat flux and dew point temperature, while decreases sensi-

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ble heat flux and near-ground temperature (Adegoke et al., 2003; Tang et al., 2007). DeAngelis et al. (2010) found the intensive groundwater pumping for agricultural use over the Great Plains leads to increased vapor which aggregates to enhance downwind precipitation. According to Ferguson and Maxwell (2012), the effect of water management (e.g., pumping and irrigation) on terrestrial water and energy budget is even comparable in magnitude to the impact of climate change (e.g., changes in temperature and precipitation). Thus, understanding the details of how irrigation affects hydrological processes will help on understanding hydrological alterations over scales, as well as providing support for conjunctive management of surface water and groundwater resources in terms of satisfying both human and environmental water needs.

While the complex feedbacks between irrigation and land surface processes have been less studied because of difficulties in observation data, the impact of large scale pumping on aquifer storage and streamflow has more apparently been observed (McGuire, 2009) and hence has been studied intensively since Theis (1940). Jenkins (1968) analyzed the stream depletion volume and residual timing of pumping by introducing SDF (Stream Depletion Factor), which measures how fast groundwater withdrawal transfers from aquifer storage to stream depletion, to account for the transient effect of pumping. Kendy and Bredehoeft (2006) assessed the response of streamflow to pumping wells with different distances to the river. They found that stream depletion caused by near-stream pumping wells quickly reaches equilibrium and responds temporally in phase with pumping; on the other hand, far-away wells cause smaller stream depletion and seasonal fluctuation, and a greater portion of the depletion occurs during post-irrigation season. They also examined the impact of irrigation efficiency on the streamflow seasonality and found that when irrigation system delivers water inefficiently, irrigation return flow recharges aquifer during the irrigation season and discharges to stream during the post-irrigation season, boosting fall and winter low flows.

Return flow to stream is a major loss of irrigation water and a major gain of streamflow under many cases. For example, Gosain et al. (2005) studied return flow from irrigation introduced by canal in Palleru river basin. They found that return flow accounts for over 50 % of irrigation application, much higher than the usual rule-of-thumb value of 10–20 %. However, in many studies, return flow is simply accounted as a fixed portion of irrigation water application and is added back to streamflow. This will probably ignore the actual quantity and temporal variation of return flow contribution to streamflow.

The combined effects of the two processes, pumping and return flow, on streamflow have not been appropriately represented by the models used for the analysis. Few current groundwater models explicitly incorporate the impact of irrigation return flow into aquifer–stream interaction; while surface hydrological models usually do not simulate the impact of groundwater pumping on baseflow appropriately. Both modeling approaches capture one aspect of the picture, but not the whole. For example, the aquifer recharge, evapotranspiration and channel loss in groundwater models are usually decided through calibration and considered fixed during simulation period. Some surface hydrological models have detailed representations of crop irrigation requirement and soil moisture, but usually assume groundwater-fed irrigation has no impact on the source (i.e., aquifer storage) (Sophocleous and Perkins, 2000). It is important to note that groundwater pumping mainly affects basin-wide hydrological quantities such as groundwater storage through groundwater movement dynamics, while irrigation affects spatially distributed processes and land–energy fluxes depending on the location of irrigated crops (Ferguson and Maxwell, 2011). The streamflow recorded at gauging stations is the result of the dynamic interactions between surface water and groundwater systems over scales, where return flow plays a critical role in partially compensating the stream depletion caused by groundwater pumping and changing the process of streamflow response to climatic variability.

In this study, SWAT is modified by linking the baseflow component to aquifer storage in order to simulate the complex effect of groundwater pumping and irrigation return flow on streamflow. The model is applied to the Frenchman Creek Basin, a sub-basin of the Republican River Basin, to assessing the streamflow change in the context of stream-aquifer interaction. Groundwater-fed irrigation has been developed in the area since 1950s and considerable streamflow depletion has been reported (Burt et al.,

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2002). Streamflow is decomposed to slow component (corresponding to a sustained baseflow from aquifer) and fast flow component (corresponding to runoff from surface and unsaturated zone, which has shorter travel time and exhibits more variability). The effects of pumping and return flow on the slow and fast components, respectively, will be analyzed from the modeling results.

2 Study area and model description

2.1 The Frenchman Creek Basin

The Republican River Basin, lying above the northern Ogallala Aquifer, is shared by Colorado, Nebraska, and Kansas. Groundwater-fed irrigation since 1950s (shown in Fig. 1 as the pumping well numbers) in this region has reduced aquifer storage and caused stream depletion problems in RRB as shown in Fig. 2. Groundwater storage in the High Plains Aquifer in 2009 was about 2.9 billion acre-ft., showing a decline of about 274 million acre-ft. (or about 9 %) from predevelopment storage (McGuire, 2011). Szilagyi (2001) found the Republican River annual streamflow has declined by 61 % without a significant change in climate. Disputes about surface water and groundwater rights lead to a legal issue among the states sharing the aquifer.

In this study, Frenchman Creek Basin, a sub-basin of RRB, is chosen as a case study for streamflow change analysis under groundwater-fed irrigation. Frenchman Creek, about 166 miles long, flows from Colorado to Nebraska. Average annual precipitation in this region from 1941 to 1994 is about 443 mm (Automated Weather Data Network http://www.hprcc.unl.edu/awdn/), which increases from east to west as the effect of elevation gradient; annual potential evapotranspiration in this region is about 1100 mm. The crop in the basin is heavily dependent on central pivot irrigation from pumping wells. Although lacking of well documented groundwater consumptive use data, studies have shown strong statistical relationship between the number of pumping wells and stream depletion in this watershed (Burt et al., 2002). In this study, the pumping is esti-

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mated with watershed model from annual irrigated crop acreage (National Agricultural Statistics Service, http://www.nass.usda.gov/Data_and_Statistics/). Frenchman Creek Basin shows a typical example of stream depletion. Majority of the flow in the basin is sustained by Ogallala Aquifer system. The perennial drainage section of the headwater, once located several miles west of Nebraska–Colorado boarder, now shrinks downstream by several miles to east of the boarder (US Department of Interior, 1996).

Streamflow decreases can be caused by aquifer pumping, but can also be explained by climate change. We first examine the climate during last decades to see if the climate can explain the streamflow change. We divide the climate time series into two equal lengths (pre- and post-1970) to examine the climate change. The spatially averaged annual precipitation and temperature since 1940s is shown in Fig. 4. The annual precipitation exhibits fluctuation ranging from 300 to 600 mm. The mean annual precipitation is 452 and 459 mm for pre-1970 and post-1970 respectively, and the standard derivation remains unchanged at around 95 mm. The annual average minimum temperature slightly increases from 1.96 to 2.13 °C, and the annual average maximum temperature slightly decreases from 18.07 to 17.92 °C. Standard derivations of the both remain unchanged at around 0.7 °C. Moreover, analyzing the trend of monthly precipitation and temperature for each decade shows no significant change in seasonal pattern. Actually, the slightly decrease in diurnal temperature range (difference between daily maximum and minimum temperature) is the result of irrigation. Irrigation leads to increased evapotranspiration and humidity above farmland, converting more radiative energy into latent heat, which results in redistribution of surface energybetween latent heat, sensible heat and ground heat flux. Adegoke et al. (2003) compared the surface energy budget between irrigated and non-irrigated farmland in High Plains. They found that due to the "cooling effect", irrigation contributes to 15 % decrease in sensible heat and 1.2 °C decrease in near-ground temperature. From the observed data, changes in climate forcing cannot fully explain the significant decrease in streamflow, which would be attributed to other factors such as land use and groundwater use.

2.2 Watershed management model

SWAT is a semi-distributed, physically-based watershed model (Arnold et al., 1998). The model includes components such as weather, hydrology, sediment transport, crop growth, water quality, and agricultural management, and has been widely applied to assessing water quantity and quality, land use and climate change impacts, and agriculture management in heterogeneous watersheds (Gassman et al., 2007). SWAT simulates runoff from surface flow, sub-surface flow and baseflow, separately. Irrigation is simulated by an auto-irrigation subroutine, i.e., irrigation is applied when the soil moisture of a crop field is below the prescribed irrigation triggering threshold during the crop growing season.

The baseflow in SWAT model is calculated by the following equation:

$$Q_{\mathrm{gw},i} = Q_{\mathrm{gw},i-1} \exp(-\alpha\Delta t) + W_{\mathrm{rchrg},i} \quad [1 - \exp(-\alpha\Delta t)], \tag{1}$$

where i is the simulation day, Δt is the time step (i.e., one day), $Q_{\mathrm{gw},i}$ is the baseflow, W_{rchrg} is the shallow aquifer recharge from soil profile, and α is the baseflow recession coefficient. By Eq. (1), baseflow depends on the baseflow in previous day (representing recession process) and recharge (representing effect of rain-induced recharge on baseflow). However, the process reflecting the impact of groundwater pumping on streamflow is missing in Eq. (1). Groundwater pumping first captures aquifer storage, if the storage is not fully recovered, then the induced water table gradient would change the discharge (i.e., baseflow), causing stream depletion. To represent this process, alternatively, the baseflow component in SWAT has been modified based on the shallow (unconfined) aquifer water storage (S_{sh}):

$$Q_{\mathrm{gw},i} = \alpha S_{\mathrm{sh},i}, \tag{2}$$

and storage is updated through shallow aquifer water balance:

$$S_{\mathrm{sh},i} = S_{\mathrm{sh},i-1} + W_{\mathrm{rchrg},i} - Q_{\mathrm{gw},i} - W_{\mathrm{revap},i} - W_{\mathrm{pump},i}, \tag{3}$$

where W_{revap} is the water evapotranspirated from shallow aquifer by deep root vegetation; W_{pump} is the water pumped from aquifer for irrigation use, which is based on the soil moisture content. Note that Eq. (2) represents a linear storage model (Te Chow et al., 1988). If there is no recharge, evapotranspiration and pumping, baseflow is an ordinary differential equation and Eq. (1) originally used in SWAT can be derived from Eqs. (2) and (3). Thus the baseflow recession parameter α is consistently used in the original and modified model. However, the modified equation requires one more parameter, the initial storage, which needs to be calibrated from observation of model outputs.

To calibrate the model for FCB, the outlet of the watershed is chosen at the upstream of Enders Reservoir (USGS siteID 06831500) to exclude the impacts of surface water regulation on streamflow. The model is calibrated and validated for 1981–1985 and 1986–1990, respectively, with multiple-objective genetic algorithm. Roots-mean-square error (RMSE) and logarithm of RMSE of streamflow are chosen as calibration criteria to consider both high flow and low flow. RMSE of crop yield is also set as criteria, mainly to calibrate the auto-irrigation trigger parameter, thus the water management activity (i.e., pumping amount and timing) is retrieved through flow and crop data. For details on model data, parameters, and calibration procedures, the reader is referred to Zeng (2012).

3 Results

3.1 Streamflow change due to land use and pumping

SWAT model is applied to three land use and water management scenarios, all under historical climate forcing data: (1) no agricultural development in this region; (2) land use change is represented by historical crop area but no irrigation (i.e., rain-fed crop); (3) historical crop area with groundwater pumping simulated by auto-irrigation in SWAT. The auto-irrigation module of SWAT calibrated to the case study watershed is used to determine the irrigation scheduling, including the water application timing and amount. By comparing the results from these scenarios, the impacts of land use and groundwater irrigation can be identified.

In the "no agricultural development" scenario, the land use is fixed as the level in 1940s, when most of the land cover in the region was either grassland or ranch and only a small fraction of the land was used for irrigated agriculture which is negligible compared to the large irrigation water consumption after quick development in the 1960s and 1970s. Under this "natural" scenario, the mean streamflow is 3.24 and 3.08 $\mathrm{m^3\,s^{-1}}$ during pre-1970s and post-1970s periods, respectively, showing a very small change. This small decline may also be caused by agricultural activity because some parts of the basin were used for crop production before 1940s.

The streamflow under agricultural development is shown in Fig. 5 with only land use change (no-irrigation scenario) and with both land use change and irrigation (irrigation scenario). For the no-irrigation scenario, the mean streamflow is 3.22 and 2.77 $\mathrm{m^3\,s^{-1}}$ during pre-1970s and post-1970s periods, respectively. For the irrigation scenario, the mean streamflow is 3.05 and 1.93 $\mathrm{m^3\,s^{-1}}$ during pre-1970s and post-1970s periods, respectively. Note that the streamflows pre-1970s are not significantly different among these scenarios, since large scale of agricultural development and groundwater pumping just started from that time. Comparing the flow post-1970s under the three scenarios shows that groundwater pumping attributes to 0.84 $\mathrm{m^3\,s^{-1}}$ decrease in streamflow, more than twice as that caused by land use at 0.31 $\mathrm{m^3\,s^{-1}}$.

3.2 Flow component change

SWAT model simulates three flow components (i.e., baseflow, subsurface flow and overland runoff), which enable us to decompose the effect of groundwater-fed irrigation on streamflow. In Fig. 5, the surface flow, subsurface flow from soil profile, and baseflow from aquifer discharge is denoted as SUR, SUB and GW, respectively. Although the streamflow decreases under both scenarios (land use only, land use and irrigation), the changes on the different flow components are significantly different. In the no-irrigation scenario, all flow components decrease, especially for the subsurface flow, which is nearly zero after 1970s. For the groundwater-fed irrigation scenario, the decrease is mainly from aquifer discharge (i.e., from 2.56 to 1.41 $\mathrm{m^3\,s^{-1}}$), while surface flow decreases slightly from 0.177 to 0.154 $\mathrm{m^3\,s^{-1}}$ and subsurface flow increases from 0.311 to 0.362 $\mathrm{m^3\,s^{-1}}$. As a result, return flow from irrigation partially compensates the stream depletion by groundwater pumping. This also implies that ignoring irrigation return flow would over-estimate stream depletion by aquifer pumping.

Aquifer discharge provides stream with a stable flow (i.e., slow flow component) and is relatively insensitive to climate variation; while surface and subsurface flow is prone to be impacted by climate variability (e.g., temperature, vapor pressure) through soil moisture dynamics, vegetation water use or human water management (Harman et al., 2011). Thus, surface and subsurface flow convert the climatic variability into streamflow variability and exhibit as fast flow components. The baseflow index (BFI, ratio of baseflow in total streamflow) is shown in Fig. 6 for irrigation and non-irrigation scenarios. The BFI decreases from 95 to 75 % due to groundwater pumping and irrigation return flow. The effects of stream depletion and irrigation return flow change the ratio of the fast and slow flow components in stream leading to changes in streamflow variability. The coefficient of variation (CoV) of streamflow in irrigation case is 0.077 and 0.151 for pre- and post-1970s, respectively. Since streamflow components are changed by crop water consumption and water management, the streamflow variability is more subjected to climate variability through of human interference rather that in a natural watershed.

3.3 Aquifer recharge-discharge pattern change

Associated with the streamflow changes, the pumping for irrigation and return flow also change the temporal pattern of aquifer storage. The increased soil moisture by irrigation application increases subsurface flow. Meanwhile the increased soil moisture also helps recharge aquifer through soil profile percolation. Figure 7 shows the soil percolation, which is considerably higher under irrigation scenario than the non-irrigation one.

Especially after 1973, the soil profile percolation is nearly zero in the non-irrigation case, since soil moisture in a large portion of the watershed is lost to atmosphere through crop evapotranspiration. While for the irrigated case, irrigation maintains soil moisture and then soil profile percolation over the years.

Aquifer storage change results from the combined effect of aquifer recharge, pumping, aquifer discharge to river and other flux (e.g., deep root vegetation evapotranspiration). The monthly aquifer storage change regime is averaged by decades, as shown in Fig. 8. During periods when irrigation intensity is low, the aquifer was recharged during summer from May to July due to precipitation-dominant recharge and discharged in winter to sustain the baseflow in streams since the precipitation is relatively low in winter. Recharge to the aquifer in summer from 1920 to 1950 is also shown by Republican River Compact Administration (RRCA) groundwater model (http://www.republicanrivercompact.org/). With agricultural development, aquifer storage experiences significant decreases in crop growth seasonal (June to September, which covers the whole summer in the region) due to pumping and high evapotranspiration. On the other hand, aquifer storage recovers during winter and spring by the return flow, which is delayed from irrigation application in summer. The maximum monthly storage decline occurs in August, in which pumping is the most intensive. Figure 9 shows the declining trend of aquifer storage during the period of 1951–1994. Aquifer storage depletion started in the 1960s, reached the maximum during the 1970s, and remained stable since then. During the 1980s, the aquifer storage depletion recovers slightly, which corresponds to the irrigation regulation within the region started in late 1980s. Thus, the intensive pumping reverses the natural seasonal groundwater recharge pattern, from "summer-recharge-and-winter-discharge" under natural conditions to "summer-discharge-and-winter-recharge" under the human interferences.

4 Conclusions

Streamflow is a result of climate forcing, catchment properties and human interferences. At the study site of this paper, streamflow records at the gauging stations reflect the synthetical effect of dynamic interactions between surface water and groundwater systems, which is enhanced by groundwater pumping and return flow in basins with heavy groundwater-fed irrigation. In this study, a modeling analysis based on modified SWAT model is applied to analyzing the conjunctive effects of pumping and irrigation return flow on streamflow. By relating baseflow to shallow aquifer storage through a linear reservoir model, the streamflow response to groundwater pumping is explicitly simulated, and the synthetical effects of the two types of human interferences, (i.e., pumping and return flow) are assessed.

While irrigation return flow compensates partially the decreases in streamflow, overall stream depletion trend due to groundwater pumping has been revealed by the model, as comparable to the observed. However, the fast flow component (surface and sub-surface flow) increases due to return flow and the slow flow component (baseflow) decreases due to groundwater pumping. As a result, the streamflow changes from a baseflow dominant regime to be one that is more influenced by surface and subsurface flow. The change among baseflow, subsurface and surface flow components due to human interferences is examined for the first time according to our knowledge, which allows a close examine of the streamflow variability, rooted with climatic variability but aggravated by human interferences (groundwater pumping and return flow). Agricultural water use in this region changes the groundwater seasonal regime from the pattern of "summer-recharge and winter-discharge" in the past to "summer-discharge and winter-recharge" at present. This challenges the existing groundwater modeling which usually assumes fixed recharge patterns and rates.

Although the modified model can simulate streamflow response to groundwater pumping, it only represents one way of the stream-aquifer interaction, that is, flow from aquifer to stream. This limits the model to simulate the situation where groundwater pumping inverses stream-aquifer interaction. This model is valid in headwater zone such as FCB, where baseflow is sustained by aquifer, but may not be applicable to areas where streamflow recharges aquifer. Also, SWAT model is semi-distributed, that is, hydrological representative units are connected with each other by the river network and no interaction exists with groundwater table gradient. Thus, assessment of aquifer storage is treated in a lumped form for the whole basin. Improvement on sub-basin aquifer storage connection would provide the spatial impact of groundwater pumping. If spatial information (e.g., impact of the location of pumping wells relative to streams, the location of drawdown cones, etc.) is included, the surface water and groundwater dynamics under human intereferences can be better understood.

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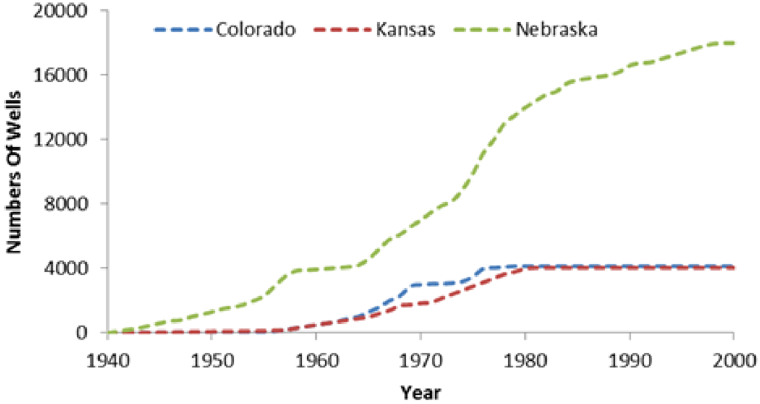

Fig. 1. Accumulative number of active groundwater pumping well of Colorado, Kansas and Nebraska in RRB (adopted from Republican River Compact Administration http://www.republicanrivercompact.org/v12p). Starting from 1960s, groundwater-fed irrigation has becomes the largest aquifer water consumption in this region.

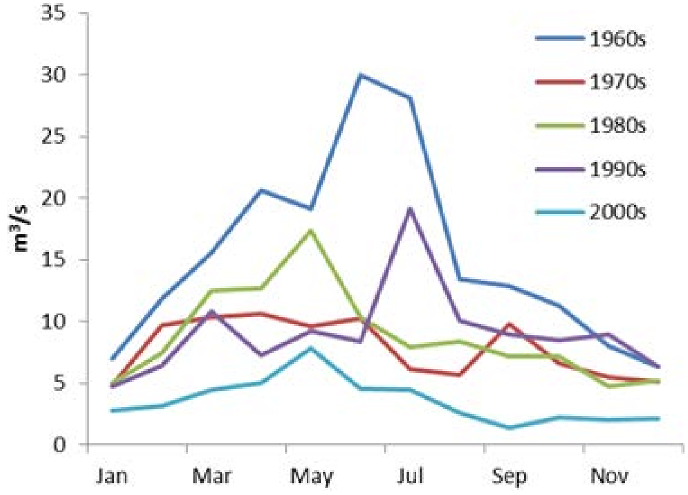

Fig. 2. Monthly flow regime (monthly average flow by each decade) at RRB outlet (Source: USGS Station 06853500).

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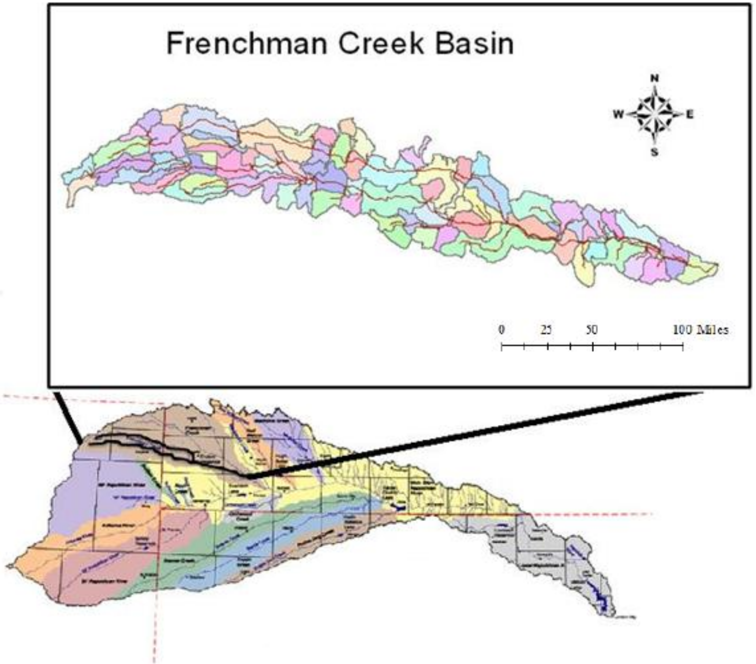

Fig. 3. Domain of Frenchman Creek Basin in Republican River Basin.

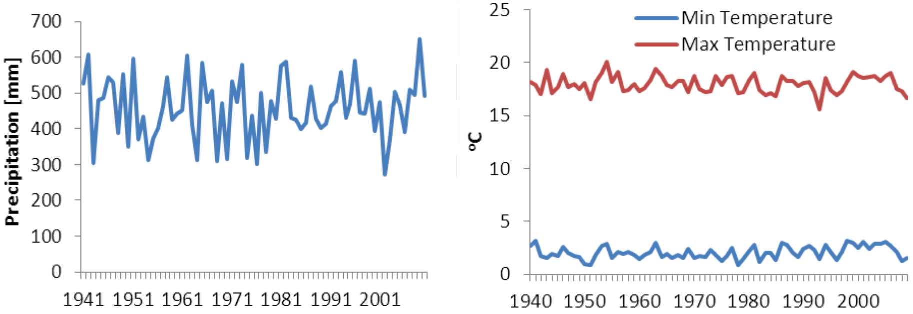

Fig. 4. Annual precipitation (left panel) and max/min temperature (right panel) in FCB. The climate exhibits no significant change during last several decades. The slight decrease in DRT implies the impact of irrigation on land surface energy redistribution.

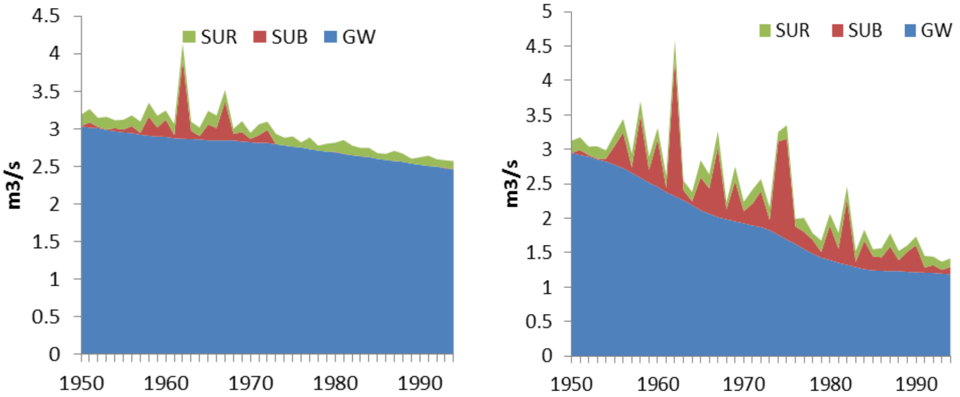

Fig. 5. Surface flow (SUR), subsurface flow (SUB) and baseflow (GW) for non-irrigation (left panel) and irrigation (right panel) case. Groundwater-fed irrigation decreases slow flow component (GW) and increases fast flow component (SUR and SUB), leading the streamflow more subjected to climate variability.

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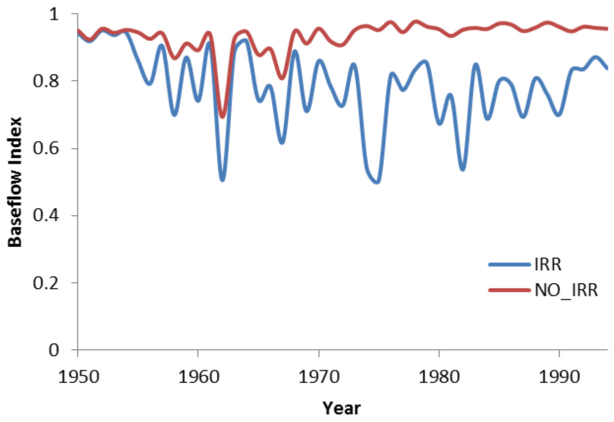

Fig. 6. Baseflow index for non-irrigation (NO-IRR) and irrigation (IRR) case.

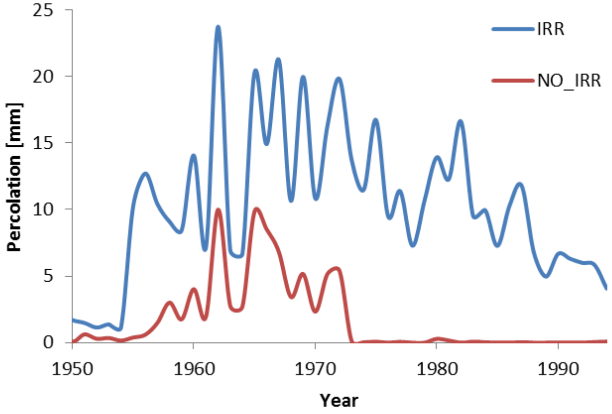

Fig. 7. Soil profile percolation for non-irrigation (NO_IRR) and irrigation (IRR) case.

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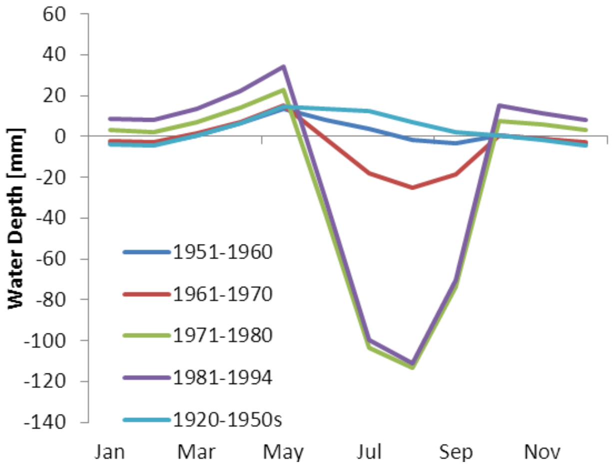

Fig. 8. Monthly aquifer storage change averaged by decades (Storage change before 1950s is not simulated in this model and is adapted from RRCA).

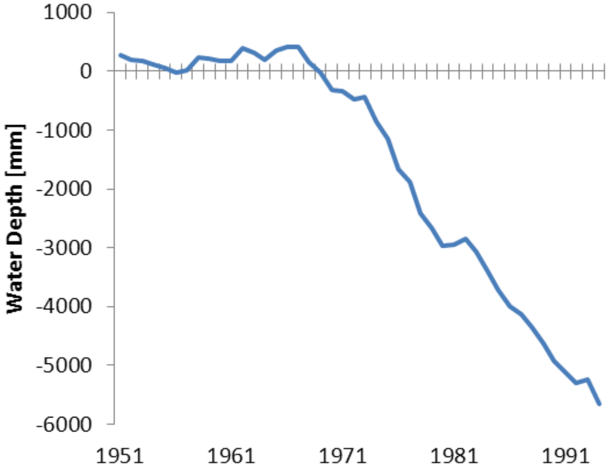

Fig. 9. Accumulative aquifer storage change.